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# Recycled Concrete Aggregates: Review Physical, Mechanical, and Durability Characterisation and Comparison with Natural Aggregates

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## Abstract

The progressive depletion of natural aggregate resources and the growing generation of construction and demolition waste (CDW) have intensified global interest in recycled concrete aggregates (RCA) as a sustainable substitute for natural aggregates (NA) in concrete production. This review synthesises quantitative data from more than fifty peer-reviewed studies published between 2012 and 2024, focusing on the physical, mechanical, and durability properties of RCA-based concrete (RAC) compared with natural aggregate concrete (NAC). Key findings indicate that RCA exhibits significantly lower apparent density (1.91 - 2.70 g/cm$^3$, average 2.32 g/cm$^3$) and substantially higher water absorption (2% - 15%) than NA (0.5% - 2%). Los Angeles abrasion values for RCA (20% - 45%) are systematically higher than those for NA (15% - 30%), reflecting increased friability attributable to adhered cement mortar (20% - 56% by mass). The compressive strength of RAC at 28 days is reduced by 2.6% - 43% relative to NAC, depending on the replacement ratio, while the modulus of elasticity decreases by up to 30%. In-service durability indicators, carbonation depth, chloride penetration, and freeze-thaw resistance are likewise adversely affected with increasing RCA content. Pretreatment methods, including accelerated carbonation, thermal treatment, and polymer impregnation, substantially improve RCA quality. The use of supplementary cementitious materials (SCMs), particularly ternary blends of Portland cement, Class F fly ash, and metakaolin or silica fume, is the most effective strategy for controlling alkali-silica reactivity (ASR) in RAC and improving overall durability. These consolidated data provide a robust basis for the development of harmonised normative specifications and circular-economy construction practices.

## Keywords

Recycled Concrete Aggregates, Sustainable Concrete, Physical-Mechanical

Properties, Durability, Circular Economy, Construction and Demolition Waste, Alkali-Silica Reaction

## 1. Introduction

The construction sector is one of the world's largest consumers of natural resources. Approximately 40 - 50 billion tonnes of natural aggregates are extracted each year globally, causing substantial environmental impacts including landscape degradation, disruption of aquatic ecosystems, and greenhouse gas emissions associated with extraction and transportation [1]. Simultaneously, the production of CDW continues to increase, accounting for 30% - 40% of total municipal solid waste in many countries [2]. Against this backdrop, the valorisation of RCA derived from demolished concrete structures represents a direct response to the principles of the circular economy in the construction sector.

RCA is produced by crushing demolished concrete elements through a series of size-reduction and sorting operations [3]. Their most distinctive characteristic, compared with NA, is the presence of residual adhered cement mortar on the aggregate surface, which can constitute 20% - 56% of their mass. This adhered mortar is the primary cause of the higher porosity, greater water absorption, and increased friability of RCA relative to NA [4] [5]. These differences affect both fresh and hardened concrete properties, which have historically limited the large-scale adoption of RCA in structural concrete applications.

Nevertheless, research conducted over the past two decades has demonstrated that, with adequate control of production processes, mix design, and the possible incorporation of SCMs, recycled aggregate concrete (RAC) can achieve performance levels sufficient for a wide range of structural and non-structural applications [6]-[8]. The specific issue of alkali-silica reaction (ASR), investigated in detail for RCA-containing concrete [9], illustrates the chemical complexity of interactions between the mineralogical composition of legacy aggregates and new cementitious matrices.

The present review aims to: i) quantitatively compare the physical and mechanical properties of RCA with those of NA; ii) analyse the influence of replacement ratio on the mechanical and durability performance of RAC; iii) catalogue the most effective pretreatment and mix optimisation strategies.

## 2. Production and Classification of Recycled Concrete Aggregates

### 2.1. Production Process

RCA production begins with the demolition of existing concrete structures. Debris is transported to crushing facilities where it undergoes a series of size-reduction operations. In a first stage, large elements (30 - 40 cm) are reduced to 30 - 40 mm fragments by a primary jaw crusher. A second crushing phase reduces these fragments to the desired aggregate size (typically 4 - 20 mm for coarse aggregates) [3]. Between stages, sorting systems remove ferrous metals (by magnetic separation), plastics, timber, and other contaminants.

The quality of the RCA produced depends strongly on the number of crushing cycles, the quality of the source concrete, and the contamination level. Research has shown that adhered mortar content decreases significantly with increasing numbers of crushing cycles, progressively aligning RCA properties with those of natural aggregates [10]. However, excessive crushing increases the proportion of fines and reduces the yield of coarse aggregate fractions.

### 2.2. Normative Classification

Several standards govern the classification and use of RCA. In Europe, EN 12620 defines aggregate requirements for concrete, and EN 206-1 specifies conditions for the use of recycled aggregates according to their class. The Dutch specification (CROW 210) and German regulation (DIN 4226-100) generally distinguish three to four RCA types based on recycled material content and contamination level. In the United States, ASTM C33 sets general requirements for concrete aggregates, although specific provisions for RCA remain less detailed than their European counterparts.

A four-category quality classification (QI to QIV) based on adhered mortar content, water absorption, and Los Angeles abrasion has been proposed, demonstrating a direct correlation between RCA quality category and RAC performance [3].

## 3. Physical Properties of Recycled vs. Natural Aggregates

**Table 1** summarises the physical properties of RCA in comparison with reference natural aggregates, consolidated from multiple experimental studies published between 2012 and 2024.

**Table 1.** Comparison of physical properties of RCA and NA.

| Property | NA (Typical Range) | RCA (Range) | Avg. Reduction (%) | Test Standard | Ref. |
|---|---|---|---|---|---|
| Apparent Density ($g/cm^3$) | 2.50 - 2.80 | 1.91 - 2.70<br>(avg. 2.32) | 5 - 18 | EN1097-6/ ASTMC127 | [2] [5] [11] |
| Water Absorption (%) | 0.5 - 2.0 | 2.0 - 15.0 | — | EN1097-6/ ASTMC127 | [2] [5] [11] |
| Bulk Density ($kg/m^3$) | 1400 - 1600 | 1150 - 1500 | 5 - 10 | EN1097-3/ ASTMC29 | [3] [11] |
| Los Angeles Abrasion (%) | 15 - 30 | 20 - 45 | 25 - 50 ↑ | EN1097-2/ ASTMC131 | [2] [3] [12] |
| Adhered Mortar Content (%) | — | 20 - 56 | — | — | [4] [5] |
| Flakiness Index | ≤ 20 | 20 - 35 | — | EN933-4 | [11] |

### 3.1. Density and Bulk Unit Weight

The apparent density of RCA is consistently lower than that of NA. Values reported in the literature range from 1.91 to 2.70 g/cm$^3$ for RCA, with an average of 2.32 g/cm$^3$ [4] [5], compared with 2.50 - 2.80 g/cm$^3$ for conventional natural aggregates [5]. This density reduction is directly attributable to adhered cement mortar, whose density (1.43 - 1.74 g/cm$^3$) is lower than that of natural rock [13]. The bulk density of RCA (1150 - 1500 kg/m$^3$) is also below that of NA (1400 - 1600 kg/m$^3$), meaning that concrete mix designs must be adjusted on a mass basis to maintain equivalent volumes [3] [11].

### 3.2. Water Absorption

Water absorption is one of the properties most significantly affected by the recycling process. RCA exhibits water absorption values of 2% - 15% [2] [5] [11], which is 4 to 10 times higher than that of NA (0.5% - 2%). This characteristic, arising directly from the higher porosity of the adhered mortar, has important practical implications: oven-dry RCA absorbs mixing water, effectively increasing the water-to-cement ratio and potentially degrading both workability and hardened concrete strength. Recent research demonstrated that the absorption rate of RCA also depends on preparation and processing procedures during crushing [9]. The Double Mixing Method (DM)—in which RCA are pre-saturated before batching—has been proposed to counteract this effect [3] [7].

### 3.3. Los Angeles Abrasion Resistance

Abrasion resistance, quantified by the Los Angeles (LA) abrasion test, is significantly lower for RCA than for NA. Reported LA coefficients for RCA range from 20% to 45%, compared with 15% - 30% for NA [2] [3]. This difference can exceed 50%, reflecting increased susceptibility to mechanical degradation. In one comparative study, LA values of 22.0% and 38.6% were measured for NA and RCA, respectively [12], consistent with general trends in the literature. Adhered mortar content is the principal explanatory factor: the mortar phase, being weaker than natural rock, fractures preferentially under impact loading in the LA drum. RCA subjected to multiple crushing cycles exhibits lower LA values, indicating improved mechanical quality [10].

## 4. Mechanical Properties of Recycled Aggregate Concrete (RAC)

Table 2 presents a comparative summary of the mechanical performance of RAC as a function of the natural-to-recycled aggregate replacement ratio.

### 4.1. Compressive Strength

Compressive strength is the most extensively studied mechanical property in the context of RAC. It has been established that the compressive strength of RAC is 2.6% - 43% lower than that of equivalent NAC, depending on the replacement ratio

[4]. The wide scatter in published results reflects the diversity of RCA sources, production methods, w/c ratios, and curing conditions. This variability was quantified by Jayasuriya *et al.* [17] using numerical simulation and statistical analysis across a large experimental database, showing that the coefficient of variation of compressive strength increases significantly with RCA replacement ratio and is closely related to the heterogeneity of adhered mortar content among aggregate particles.

**Table 2.** Comparative mechanical properties of NAC and RAC as a function of replacement ratio (values at 28 days under standard curing conditions).

| Mechanical Property | NAC (Reference) | RAC 25% RCA | RAC 50% RCA | RAC 100% RCA | Ref. |
|---|---|---|---|---|---|
| Compressive Strength fc28 (MPa) | ~40 | 38 - 40 | 33 - 38 | 23 - 39 | [4] [5] [7] [14] [15] |
| Splitting Tensile Strength (MPa) | 3.0 - 4.0 | 2.9 - 3.9 | 2.7 - 3.6 | 2.4 - 3.2 | [5] [7] [15] |
| Modulus of Elasticity (GPa) | 30 - 35 | 28 - 33 | 25 - 30 | 21 - 27 | [5] [7] [15] [16] |
| Flexural Strength (MPa) | 4.5 - 5.5 | 4.3 - 5.2 | 4.0 - 4.9 | 3.8 - 4.7 | [5] [7] [14] |
| Slump (mm) | 80 - 120 | 70 - 110 | 60 - 100 | 50 - 90 | [5] [7] [11] |

Several mechanisms contribute to this reduction: i) the double interfacial transition zone (double ITZ) characteristic of RAC, which is weaker than the single ITZ in NAC; ii) the intrinsic porosity of the adhered mortar; iii) micro-cracks generated during crushing [8]. Notably, it has been demonstrated that despite higher free drying shrinkage, concrete made with 25% RCA replacement may exhibit reduced cracking susceptibility under restrained conditions [18]. However, strengths comparable to NAC can be achieved through optimisation of the w/c ratio, pre-saturation of RCA, or incorporation of SCMs [7] [15]. Over the long term (5 years), the compressive strengt h gain of RAC can exceed that of NAC, with increases of 62% versus 34% reported in the literature [19], suggesting beneficial ongoing pozzolanic reactions within the recycled matrix.

## 4.2. Modulus of Elasticity

The modulus of elasticity is the mechanical property most severely affected by recycling. A systematic review of 121 publications (1973-2015) showed that elastic modulus can be reduced by up to 30% at a 100% RCA replacement level [16]. This reduction is primarily attributed to the lower stiffness of adhered mortar and the reduced density of RCA [7] [15].

## 4.3. Tensile and Flexural Strength

Splitting tensile strength and flexural strength of RAC are also reduced relative to NAC, but generally to a lesser degree than compressive strength. Tensile strength may decrease by 5% - 18% with increasing RCA content [5] [7] [15], while flexural strength is reduced by up to 15% [5] [7] [14]. The incorporation of reinforcing fibres (polyethylene fibres at 0.3%) has been shown to improve the tensile strength of RAC by 10%, partially offsetting the effects of recycled content [7].

### 4.4. Workability

The workability of fresh RAC, measured by slump, is generally reduced in the presence of RCA due to the higher water absorption of the aggregates. At the same nominal w/c ratio, slump can decrease by 10% - 25% at 100% RCA [5] [7] [11]. This limitation can be addressed by RCA pre-saturation (double mixing method) or by the addition of superplasticisers.

## 5. Durability Properties of Recycled Aggregate Concrete

**Table 3** summarises the key durability indicators of RAC compared with NAC, consolidated from the reviewed literature.

**Table 3.** Comparative durability properties of NAC and RAC.

| Durability Indicator | NAC | RAC 50% RCA | RAC 100% RCA | Comments/Ref. |
|---|---|---|---|---|
| Water Absorption of Hardened Concrete (%) | 3 - 5 | 5 - 7 | 6 - 10 | Increases with substitution rate [8] [11] |
| Carbonation Depth (mm/year 0.5) | 3 - 6 | 6 - 10 | 8 - 15 | Related to RCA porosity [6] [8] |
| Chloride Penetration (C/coulombs) | 500 - 1500 | 1500 - 3000 | 2000 - 4500 | Reduced by accelerated carbonation [6] |
| Freeze-Thaw Resistance (mass loss, %) | <5 | 5 - 15 | 10 - 20 | Double ITZ weakens the concrete [2] |
| Abrasion Resistance (mass loss, %) | <3 | 3 - 7 | 5 - 12 | Correlated with mortar content [12] |

### 5.1. Carbonation

Carbonation is one of the most studied degradation mechanisms in RAC. Carbonation depth increases with the RCA replacement ratio, owing to the greater accessible porosity of RCA and the more open microstructure of the cement paste. Carbonation depths 2 - 3 times greater than those of equivalent NAC have been observed for RAC at 100% RCA [6] [8]. Paradoxically, accelerated carbonation treatment of RCA is an effective pretreatment method for densifying the microstructure and reducing water absorption, as $CO_2$ reacts with $Ca(OH)_2$ and C-S-H to form $CaCO_3$ that clogs micropores [6].

### 5.2. Chloride Penetration Resistance

Chloride ion penetration, which governs the service life of reinforced concrete structures in aggressive environments, is significantly higher in RAC than in NAC. Accelerated carbonation of RCA has been shown to reduce chloride penetration depths and may extend structural service life by up to 28% in chloride-rich marine environments [6]. The incorporation of fly ash (20% - 40% cement replacement) markedly improves chloride penetration resistance in RAC through secondary C-S-H formation that densifies the microstructure [8].

### 5.3. Freeze-Thaw Resistance

Freeze-thaw resistance of RAC is generally lower than that of NAC owing to the more permeable double ITZ and the higher porosity of RCA. Greater mass losses and larger reductions in residual strength after freeze-thaw cycling have been observed for RAC, particularly at replacement ratios above 50% [2]. The incorporation of air-entraining admixtures and SCMs (silica fume, metakaolin) has been identified as an effective solution for improving the freeze-thaw resistance of RAC [2] [8].

### 5.4. Alkali-Silica Reaction (ASR)

Alkali-silica reactivity (ASR) in RAC is a specific issue documented in detail in the literature [9]. RCA may carry reactive siliceous minerals inherited from source concrete, potentially leading to ASR expansion levels exceeding those observed with comparable natural aggregates. ASTM C1260 and ASTM C1567 testing showed that ASR expansion can be up to 100% greater in RAC than in comparable natural-aggregate concrete, depending on the processing level of the RCA [9]. The processing of RCA significantly affects expansion variability, and modifications to standard mixing and preparation procedures for ASTM C1260 testing of RCA have been recommended [9]. An earlier foundational study confirmed that the accelerated mortar bar test (AMBT, ASTM C1260) is applicable to RCA reactivity testing but requires careful attention to crushing procedures; seven different RCA sources were evaluated, confirming the applicability of the test but highlighting the sensitivity to processing [20].

SCMs—particularly ternary blends combining Portland cement, Class F fly ash, and metakaolin or silica fume—are the most effective strategy for controlling ASR in RAC [9]. A 40% replacement of Portland cement with Class F fly ash was found to reduce expansion below the critical 0.10% threshold defined by ASTM C1260 in concrete containing 100% of a highly reactive RCA.

## 6. Methods for Improving Recycled Aggregate Properties

**Table 4** presents a synthesis of the main RCA pretreatment methods documented in recent literature, with their respective advantages and limitations.

**Table 4.** Main pretreatment methods for recycled concrete aggregates and their effects on RAC properties.

| Method | Principle | Observed Improvements | Drawbacks/ Limitations |
|---|---|---|---|
| Thermal Treatment | Heating at 300˚C - 600˚C + mechanical impact | 30% - 50% reduction in water absorption | High energy cost |

**Continued**

| | | | |
|---|---|---|---|
| Accelerated Carbonation | $CO_2$ exposure under pressure | 28% reduction in chloride penetration; pore densification | Requires specialised equipment |
| Acid Treatment ($HCl/H_2SO_4$) | Dissolution of adhered mortar | 5% - 8% increase in aggregate density | Environmental impact; corrosion risk |
| Polymer Impregnation (PCC) | Pore filling with polymer | Compressive strength +20% | High material cost |
| Double Mixing (DM) | Pre-saturation of RCA before mixing | Compressive strength +10% - 15% | Longer batching process |

### 6.1. Mechanical Treatments

Mechanical treatments aim to reduce adhered mortar content through abrasion or impact. Attrition treatment and multiple crushing allow partial detachment of the mortar layer, thereby improving RCA density and reducing water absorption [3] [10]. These methods are relatively straightforward to implement in existing crushing facilities but generate additional fines and have limited efficiency (20% - 30% reduction in mortar content).

### 6.2. Thermal Treatment

Thermal treatment at 300˚C - 600˚C softens the adhered mortar, which can then be more readily removed by mechanical impact. Reductions of 30% - 50% in water absorption have been reported following thermal treatment [12]. However, the high energy cost of this approach can compromise the overall environmental balance of RCA.

### 6.3. Accelerated Carbonation

Accelerated carbonation involves exposing RCA to a $CO_2$-enriched atmosphere (typically 99% concentration) under pressure. $CO_2$ reacts with unhydrated cementitious phases in the adhered mortar ($Ca(OH)_2$, C-S-H) to form $CaCO_3$, which seals micropores and hardens the aggregate surface. Significant reductions in water absorption and chloride permeability have been observed, with potential extension of structural service life by 28% in marine environments [6]. This method additionally sequesters $CO_2$, improving the carbon footprint of the recycling process [1].

### 6.4. Supplementary Cementitious Materials (SCMs)

The incorporation of SCMs into RAC mixes is the most widely applied and best-documented improvement strategy. Class F fly ash (20% - 40% substitution), silica fume (5% - 15%), and metakaolin (10% - 20%) improve both the mechanical properties and durability of RAC. Ternary blends (cement + fly ash + metakaolin or silica fume) have demonstrated the best overall performance, particularly for ASR mitigation [9], carbonation resistance [8], and chloride resistance [6] [8]. The addition of 20% fly ash in RAC containing reactive RCA improved bond strength by 10% relative to untreated RAC [6].

## 7. Discussion

### 7.1. Synthesis of Comparative Performance

The data reviewed confirm that RCA exhibits inferior properties to NA across virtually all physical and mechanical indicators. However, the magnitude of these differences is strongly dependent on the quality of the source concrete, crushing and sorting procedures, and end-use conditions. The heterogeneity of published results—illustrated by the wide range of compressive strength reductions (2.6% - 43%)—argues for better standardisation of test methods and RCA classification specifications.

An important area of consensus concerns the replacement ratio: at rates below 30%, property reductions are generally small and within acceptable limits for common structural applications, provided that the RCA meets the quality requirements of exposure class XC1 - XC2 as defined in EN 206:2013+A2:2021 and that the target compressive strength class does not exceed C30/37 [4] [5] [7] [14]. Beyond 50% and up to 100%, compensatory measures (SCMs, pretreatment, w/c adjustment) become necessary to maintain adequate performance [4] [5] [7] [14].

### 7.2. Environmental and Economic Perspectives

From a life-cycle perspective, the use of RCA reduces the environmental impacts associated with natural aggregate extraction and CDW landfilling. As cement production accounts for approximately 8% of global anthropogenic GHG emissions [1], the combination of RCA with SCMs constitutes a dual decarbonisation strategy for the construction sector. Cost savings of up to 60% have been documented for the substitution of natural aggregates with recycled alternatives, primarily owing to reduced transportation costs [1].

### 7.3. Research Gaps and Future Needs

Several gaps persist in the literature. First, studies reporting long-term (>5 years) properties of RAC remain scarce. Second, data on RAC performance under extreme climatic conditions (arid, tropical humid) are insufficient. Third, standardisation of methods for quantifying adhered mortar content requires consolidation. Predictive modelling of RAC properties from RCA characteristics would improve the reliability of structural design with recycled materials. The statistical database developed by Jayasuriya *et al.* [21] represents a valuable step in this direction by enabling quantification of property scatter and derivation of probabilistic design relationships. Numerical mesoscale approaches, including the stochastic Monte Carlo framework [22] and random aggregate generation method [23], offer additional tools for interpreting the variability documented [17]. The specific cracking susceptibility of RCA concrete [18] also deserves further study under restrained conditions representative of real structural elements. Finally, regional variability in RCA composition [3] calls for region-specific characterisation studies to complement the global datasets reviewed here.

## 8. Conclusions

This review has provided a comprehensive quantitative overview of the physical, mechanical, and durability properties of recycled concrete aggregates in comparison with natural aggregates. The principal conclusions are as follows:

- The apparent density of RCA (1.91 - 2.70 g/cm$^3$, average 2.32 g/cm$^3$) is 5% - 18% lower than that of NA, owing to residual adhered cement mortar (20% - 56% by mass).
- The water absorption of RCA (2% - 15%) is 4 - 10 times higher than that of NA (0.5% - 2%), necessitating systematic corrections during mix design.
- The Los Angeles abrasion coefficient of RCA (20% - 45%) is 25% - 50% higher than that of NA (15% - 30%), indicating increased friability attributable to the mortar phase.
- The 28-day compressive strength of RAC is reduced by 2.6% - 43%, depending on the replacement ratio; the modulus of elasticity decreases by up to 30% at 100% RCA.
- Durability of RAC is adversely affected by in-service carbonation, increased chloride penetration, and reduced freeze-thaw resistance; these effects are mitigated by SCMs and RCA pretreatment.
- Alkali-silica reactivity, specifically documented for RAC, is most effectively controlled by ternary blends associating Portland cement, Class F fly ash, and metakaolin or silica fume.
- Accelerated carbonation, thermal pretreatment, and the double mixing method are the most effective approaches for improving RCA and RAC performance.

In summary, these findings confirm the viability of RCA as a substitute material for a wide range of construction applications, provided appropriate characterisation, adjusted mix design, and rigorous quality control are implemented. The development of harmonised international normative specifications grounded in consolidated quality indicators represents the critical next step towards mainstreaming RCA in sustainable construction.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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